

Stein embedding theorem for \mathbb{B} -manifolds

P.M. Gadea, J. Grifone, J. Muñoz Masqué ^{*†‡}

Abstract

An analog to the Stein embedding theorem for C^∞ manifolds endowed with two equidimensional supplementary foliations, is proved.

1 Introduction

The aim of this paper is to provide an intrinsic characterization of the smooth manifolds endowed with two equidimensional supplementary foliations, which admit a closed embedding into an affine space $\mathbb{R}^{2N} = \mathbb{R}^N \times \mathbb{R}^N$, equipped with its natural pair of foliations corresponding to $\langle \partial/\partial x_1, \dots, \partial/\partial x_N \rangle$ and $\langle \partial/\partial y_1, \dots, \partial/\partial y_N \rangle$.

Such a class of manifolds appears in a natural way in different geometric settings, and they are designated by distinct names in the specialized literature, as paracomplex manifolds, hyperbolic complex manifolds, etc.; see, among others, the survey paper [2] and the references mentioned therein, and for the corresponding homogeneous and symmetric spaces see also [1, 4, 9, 10, 12]. In studying these manifolds, we obtain an interesting relationship between \mathbb{B} -holomorphy and foliations, \mathbb{B} being the quadratic algebra of double numbers (see §2). For the theory of A -holomorphy and A -analyticity on a finite-dimensional commutative \mathbb{R} -algebra A , we refer the reader to [5, 11, 15, 16, 18]. Such notions allow one to define the category of A -manifolds of class C^r , $r \in \mathbb{N}$ or $r \in \{\infty, \omega\}$, which are C^r manifolds endowed with a subsheaf of A -algebras of the sheaf of germs of A -valued smooth functions; see [14] for a general exposition on the topic, and also [6] for the particular case $A = \mathbb{B}$.

On a manifold M , the structure given by two equidimensional supplementary distributions $T^-(M)$ and $T^+(M)$, defines a sheaf of \mathbb{B} -algebras, denoted by \mathcal{B}_M^∞ and called the sheaf of J -holomorphic \mathbb{B} -valued functions on M (see §2.(d)), which in the integrable case (*i.e.*, when $T^-(M)$, $T^+(M)$ are involutive) completely determines both distributions. Hence a manifold equipped with two equidimensional supplementary foliations can be understood as a sort of complex manifold over \mathbb{B} .

^{*}Partially supported by the DGICYT, Spain, under Grant BFM2002-0141.

[†]The first author is grateful to the Laboratoire “Emile Picard”, Université Paul Sabatier, Toulouse, by its kind hospitality.

[‡]2000 *Mathematics Subject Classification*. Primary 30G35; Secondary 16P10, 26E05, 32E10, 53C12, 57R30.

Quite surprisingly, the original topological embedding problem can then be reformulated in terms of the ringed manifold $(M, \mathcal{B}_M^\infty)$ by imposing three conditions, which—at least formally—exactly coincide with Stein’s conditions for a complex manifold. The geometric meaning of such conditions is however rather different, as they refer to the topology of the underlying foliations; especially, the notion of convex holomorphy needs to be suitably translated to \mathbb{B} -manifolds.

Accordingly, our main result (Theorem 4.1) is stated as an analog to Stein’s theorem—intrinsically characterizing closed analytic submanifolds of \mathbb{C}^{2n+1} (*e.g.*, see [8, Theorem 5.3.9], [7, Theorem VII.C.10])—for the category of such doubly foliated manifolds. Nevertheless, its proof is completely different to that of the complex case, because the basic tools of the standard proof (such as [8, Lemmas 5.3.4, 5.3.5]) do not work at all in the present setting, as the ground ring \mathbb{B} is not a field. In fact, the version of Stein’s theorem for \mathbb{B} -manifolds M presented below can basically be understood as a criterion for the quotients $M/T^-(M)$, $M/T^+(M)$ to exist (see §3) and this criterion is expressed in terms of the intrinsic properties of the ring of \mathbb{B} -holomorphic functions on the \mathbb{B} -manifold M , even in the case of non-compact leaves.

2 Definitions and preliminaries

In this section we give the definition of \mathbb{B} -manifolds and several results (without proof) concerning their rings of functions: \mathbb{B} -differentiable, \mathbb{B} -holomorphic, and \mathbb{B} -analytic functions. Let $\mathbb{B} = \mathbb{R}[x]/(x^2 - 1) = \{z = x + jy : x, y \in \mathbb{R}, j^2 = 1\}$ be the algebra of double numbers (see [2]). We denote by $\bar{z} = x - jy$ the conjugate of the element $z = x + jy \in \mathbb{B}$, and by $|z|$ its Euclidean norm.

2.1 \mathbb{B} -differentiability and \mathbb{B} -holomorphy

Definition 2.1. Let $U \subseteq \mathbb{B}$ be an open subset. A function $F: U \rightarrow \mathbb{B}$ is said to be \mathbb{B} -differentiable if for every $z_0 \in U$ the following limit exists in \mathbb{B} :

$$\lim_{\substack{z \rightarrow z_0 \\ z - z_0 \in \mathbb{B}^*}} \frac{F(z) - F(z_0)}{z - z_0},$$

where $\mathbb{B}^* = \{z \in \mathbb{B} : x^2 \neq y^2\}$ is the group of invertible elements. More generally, a function $F: U \rightarrow \mathbb{B}$, defined on an open subset $U \subseteq \mathbb{B}^n$, is said to be \mathbb{B} -differentiable if the function $z \mapsto F(z_1, \dots, z_{i-1}, z, z_{i+1}, \dots, z_n)$, is \mathbb{B} -differentiable on its domain for every $i = 1, \dots, n$. The function $F: U \rightarrow \mathbb{B}$ is said to be \mathbb{B} -holomorphic if it is of class C^∞ and \mathbb{B} -differentiable. We denote by $\mathcal{B}^\infty(U)$ the algebra of \mathbb{B} -holomorphic functions on U .

We have

Proposition 2.2. *A basis of the module of \mathbb{B} -derivations of the ring $C^\infty(U, \mathbb{B}) = C^\infty(U) \otimes_{\mathbb{R}} \mathbb{B}$ is the following:*

$$\frac{\partial}{\partial z_i} = \frac{1}{2} \left(\frac{\partial}{\partial x_i} + j \frac{\partial}{\partial y_i} \right), \quad \frac{\partial}{\partial \bar{z}_i} = \frac{1}{2} \left(\frac{\partial}{\partial x_i} - j \frac{\partial}{\partial y_i} \right), \quad 1 \leq i \leq n,$$

where $z_i = x_i + jy_i$. This is the basis dual to $(dz_i, d\bar{z}_i)$, $1 \leq i \leq n$.

Proposition 2.3. A function $F \in C^\infty(U, \mathbb{B})$ is \mathbb{B} -holomorphic if and only if, for every $1 \leq i \leq n$, we have $\partial F / \partial \bar{z}_i = 0$; or equivalently, $dF = \sum_{i=1}^n (\partial F / \partial z_i) dz_i$.

2.2 \mathbb{B} -analyticity

Definition 2.4. A function $F: U \rightarrow \mathbb{B}$ on an open subset $U \subseteq \mathbb{B}^n$ is said to be \mathbb{B} -analytic if for every $z^0 = (z_1^0, \dots, z_n^0) \in U$ there exists a series

$$\sum_{\alpha \in \mathbb{N}^n} b_\alpha z_1^{\alpha_1} \dots z_n^{\alpha_n} \in \mathbb{B}[[z_1, \dots, z_n]]$$

absolutely convergent in a polydisk $|z_i| \leq r_i$, $1 \leq i \leq n$, such that

$$F(z) = \sum_{\alpha \in \mathbb{N}^n} b_\alpha (z_1 - z_1^0)^{\alpha_1} \dots (z_n - z_n^0)^{\alpha_n},$$

for every $z = (z_1, \dots, z_n) \in U$, $|z_i - z_i^0| < r_i$, $1 \leq i \leq n$. We denote by $\mathcal{A}(U)$ the algebra of \mathbb{B} -analytic functions on U .

We have (see [5, Proposition 2.5])

Proposition 2.5. A \mathbb{B} -holomorphic function $F: U \rightarrow \mathbb{B}$ on an open subset $U \subseteq \mathbb{B}^n$ is \mathbb{B} -analytic if and only if it is of class C^ω ; that is, $\mathcal{A}(U) = \mathcal{B}^\infty(U) \cap C^\omega(U, \mathbb{B})$.

2.3 \mathbb{B} -manifolds

Definition 2.6. An almost \mathbb{B} -manifold of class C^∞ (resp. C^ω) is a C^∞ (resp. C^ω) manifold and a tensor field J on M of class C^∞ (resp. C^ω) and type $(1, 1)$ such that: (1) $J^2 = \text{id}$, (2) the subbundles of J -eigenvectors, $T^-(M)$ and $T^+(M)$, of eigenvalues -1 and $+1$, respectively, have the same rank. An almost \mathbb{B} -manifold is said to be a \mathbb{B} -manifold if the distributions defined by $T^-(M)$ and $T^+(M)$ are involutive. A map $f: (M, J) \rightarrow (M', J')$ between almost \mathbb{B} -manifolds is said to be J -holomorphic (cf. [10]) if $f_* \circ J_x = J'_{f(x)} \circ f_*$ for all $x \in M$.

Almost \mathbb{B} -manifolds (resp. \mathbb{B} -manifolds) are usually called almost paracomplex (resp. paracomplex) manifolds. The terminology in the present paper is due to the fact that we would like to emphasize that they are manifolds modelled over free modules over the ring \mathbb{B} (see [6]).

Example 2.7. We define two \mathbb{B} -manifold structures on an open subset $U \subseteq \mathbb{B}^n$. The *first canonical \mathbb{B} -structure* is: $J(\partial/\partial x_i) = \partial/\partial y_i$, $J(\partial/\partial y_i) = \partial/\partial x_i$, $1 \leq i \leq n$; the *second canonical \mathbb{B} -structure* is (see [10]): $I(\partial/\partial x_i) = \partial/\partial x_i$, $I(\partial/\partial y_i) = -\partial/\partial y_i$, $1 \leq i \leq n$. They are distinct but isomorphic, as the map $\Psi: \mathbb{B}^n = \mathbb{R}^n \times \mathbb{R}^n \rightarrow \mathbb{B}^n$, $\Psi(u, v) = \frac{1}{2}(u + v) + \frac{1}{2}j(u - v)$, transforms I into J ; that is, $\Psi_* \circ I = J \circ \Psi_*$.

Note that in Theorem 3.5 below the first canonical \mathbb{B} -structure above J is used, whereas in Theorem 3.8 below the second one I appears.

2.4 \mathbb{B} -manifolds as ringed spaces

Proposition 2.8. *Let (M, J) be a smooth almost \mathbb{B} -manifold. A map F from (M, J) to (\mathbb{B}, J) is J -holomorphic if and only if there exist functions $f, g \in C^\infty(M)$ such that: (1) $F = (1 + j)f + (1 - j)g$, and (2) f and g are first integrals of $T^-(M)$ and $T^+(M)$, respectively; that is, $X^-(f) = 0$, $X^+(g) = 0$, for all $X^- \in \Gamma(T^-(M))$, $X^+ \in \Gamma(T^+(M))$. We denote by \mathcal{B}_M^∞ the sheaf on germs of J -holomorphic \mathbb{B} -valued functions on M .*

This notion is consistent with §2.(a) by virtue of the following result:

Proposition 2.9. *A $2n$ -dimensional almost \mathbb{B} -manifold (M, J) of class C^∞ is a \mathbb{B} -manifold if and only if its sheaf of germs of J -holomorphic functions is locally isomorphic to the sheaf of germs of \mathbb{B} -holomorphic functions on \mathbb{B}^n ; that is, if and only if M admits an open covering $\{U_\alpha\}_{\alpha \in A}$ such that there exists an isomorphism $\varphi_\alpha: U_\alpha \rightarrow \mathbb{B}^n$ of almost \mathbb{B} -manifolds between U_α and an open subset of \mathbb{B}^n , for each α .*

Therefore

Proposition 2.10. *A differentiable map $f: M \rightarrow M'$ between smooth \mathbb{B} -manifolds is J -holomorphic if and only if for every open subset $U' \subseteq M'$ and every $F' \in \mathcal{B}^\infty(U')$, the composite map $F' \circ f$ belongs to $\mathcal{B}^\infty(f^{-1}U')$.*

Example 2.11. Let X, Y be two C^∞ differentiable manifolds of the same dimension n . In $M = X \times Y$ there exists a unique structure of \mathbb{B} -manifold such that for each pair of open subsets $U \subset X$, $V \subset Y$, the ring of \mathbb{B} -holomorphic functions on M defined on $U \times V$ is $\{(1 + j)f \circ p^- + (1 - j)g \circ p^+ : f \in C^\infty(U), g \in C^\infty(V)\}$, where $p^-: M = X \times Y \rightarrow X$ and $p^+: M = X \times Y \rightarrow Y$ are the canonical projections.

2.5 \mathbb{B} -complexification

If (M, J) is a $2n$ -dimensional \mathbb{B} -manifold of class C^∞ , for every $x \in M$ we set $T_x^\mathbb{B}(M) = T_x(M) \otimes_{\mathbb{R}} \mathbb{B}$, and extend J to $T_x^\mathbb{B}(M)$ by simply setting $J^\mathbb{B}(X + jY) = JX + jJY$. Dually, we set $T_x^{*\mathbb{B}}(M) = T_x^*(M) \otimes_{\mathbb{R}} \mathbb{B}$, and extend J^* to $T_x^{*\mathbb{B}}(M)$, accordingly. We define

$$T_x^{1,0}(M) = \{Z \in T_x^\mathbb{B}(M) : J^\mathbb{B}(Z) = jZ\}, \quad T_x^{0,1}(M) = \{Z \in T_x^\mathbb{B}(M) : J^\mathbb{B}(Z) = -jZ\}.$$

Then, we have

1. $T_x^\mathbb{B}(M) = T_x^{1,0}(M) \oplus T_x^{0,1}(M)$.
2. If $(z_i)_{1 \leq i \leq n}$ is a \mathbb{B} -coordinate system on an open neighbourhood U of $x \in M$, then $((\partial/\partial z_i)_x)_{1 \leq i \leq n}$ (resp. $((\partial/\partial \bar{z}_i)_x)_{1 \leq i \leq n}$) is a basis of $T_x^{1,0}$ (resp. $T_x^{0,1}$) (see Propositions 2.2 and 2.9).
3. $T_x^{*\mathbb{B}}(M) = T_x^{*1,0}(M) \oplus T_x^{*0,1}(M)$.

4. If $(z_i)_{1 \leq i \leq n}$ is as in item 2, then $(d_x z_i)_{1 \leq i \leq n}$ (resp. $(d_x \bar{z}_i)_{1 \leq i \leq n}$) is a basis of $T_x^{*1,0}(M)$ (resp. $T_x^{*0,1}(M)$).
5. If $F \in \mathcal{B}^\infty(M)$, then $d_x F \in T_x^{*1,0}(M)$ (cf. Proposition 2.3).

3 Stein \mathbb{B} -manifolds

Theorem 3.1. *Let (M, J) be a C^∞ \mathbb{B} -manifold such that the quotient manifolds $M^- = M/T^-(M)$, $M^+ = M/T^+(M)$ exist in the category of C^∞ manifolds. For every $x \in M$, let \mathcal{F}_x^- (resp. \mathcal{F}_x^+) be the leaf of $T^-(M)$ (resp. of $T^+(M)$) through x , and let us endow $M^- \times M^+$ with the \mathbb{B} -structure given in Example 2.11. We have (1) The map $\varphi: M \rightarrow M^- \times M^+$ defined by $\varphi(x) = (\mathcal{F}_x^-, \mathcal{F}_x^+)$ is an open immersion of \mathbb{B} -manifolds. (2) If either every \mathcal{F}_x^+ is compact and M^- is simply connected or every \mathcal{F}_x^- is compact and M^+ is simply connected, then φ is an open embedding. (3) If for every couple $x \neq y \in M$, there is $F \in \mathcal{B}^\infty(M)$ such that $F(x) \neq F(y)$, then φ is an open embedding.*

Proof. (1) Let $p^-: M \rightarrow M^-$ and $p^+: M \rightarrow M^+$ be the quotient mappings. As is well known, p^+ and p^- are submersions of C^∞ manifolds ([13, I.§5.Theorem X]) such that $\text{Ker } p_*^- = T^-(M)$ and $\text{Ker } p_*^+ = T^+(M)$. We have $\varphi = (p^-, p^+)$. Hence $\varphi_* X = 0$ for $X \in T(M)$ implies $p_*^-(X) = 0$ and $p_*^+(X) = 0$, and consequently $X = 0$. It thus follows that φ is an immersion and since $\dim M = \dim(M^- \times M^+)$, we conclude that φ is an open immersion. (2) Assume that every leaf \mathcal{F}_x^+ is compact and M^- is simply connected. Let $\pi: \mathcal{F}_x^+ \rightarrow M^-$ be the restriction to the leaf of the quotient mapping $p^-: M \rightarrow M^-$. Since $\text{Ker } p_*^- = T^-(M)$, π is a local diffeomorphism, and since \mathcal{F}_x^+ is connected and compact it follows that π is surjective; hence π is a covering map and by virtue of the hypothesis π is a global diffeomorphism. Accordingly, the relations $\mathcal{F}_x^- = \mathcal{F}_y^-$ (i.e., $y \in \mathcal{F}_x^-$) and $\mathcal{F}_x^+ = \mathcal{F}_y^+$ (i.e., $\pi(x) = \pi(y)$), imply $x = y$. Therefore φ is injective. (3) We only need to prove that either $\mathcal{F}_x^- \neq \mathcal{F}_y^-$ or $\mathcal{F}_x^- = \mathcal{F}_y^-$. Consider the function $F = (1+j)f + (1-j)g$, where f and g are first integrals of $T^-(M)$ and $T^+(M)$, respectively. Assume $\mathcal{F}_x^- = \mathcal{F}_y^-$ (or equivalently, $y \in \mathcal{F}_x^-$). Then $g(x) = g(y)$. Similarly, $\mathcal{F}_x^+ \neq \mathcal{F}_y^+$ implies $f(x) = f(y)$, and the result follows from our hypothesis. \square

Remark 3.2. The quotient manifolds M^- and M^+ may exist and however φ may not be injective. For example, take $M = \{(z, w) \in \mathbb{C}^2 : w \neq 0\}$, endowed with the \mathbb{B} -structure defined by the fibres of the projections $p^-: M \rightarrow \mathbb{C}$ and $p^+: M \rightarrow \mathbb{C}$ defined by $p^-(z, w) = z$ and $p^+(z, w) = z + w^2$. Then M^- and M^+ exist and both coincide with \mathbb{C} . Nevertheless $\mathcal{F}_{(z,w)}^- \cap \mathcal{F}_{(z,w)}^+ = \{(z, w), (z, -w)\}$ for every $(z, w) \in M$. In the general case, $\mathcal{F}_x^- \cap \mathcal{F}_x^+$ is a discrete subset of M , since \mathcal{F}_x^- and \mathcal{F}_x^+ cut transversally at each point $x \in \mathcal{F}_x^- \cap \mathcal{F}_x^+$, and $T_x(\mathcal{F}_x^-) \cap T_x(\mathcal{F}_x^+) = \{0\}$. We set $\nu(M) = \sup_{x \in M} \#(\mathcal{F}_x^- \cap \mathcal{F}_x^+)$ (this is a positive integer or ∞). Assume $M/T^-(M)$ and $M/T^+(M)$ exist in the category of C^∞ -manifolds. Then a necessary and sufficient condition for M to be an open subset of the product \mathbb{B} -structure defined in Theorem 3.1, is $\nu(M) = 1$.

Corollary 3.3. *Under the hypotheses of Theorem 3.1-(1), M admits a compatible structure of \mathbb{B} -analytic manifold.*

Proof. From Whitney's Theorem on C^ω analytization and Proposition 2.5 it follows that $M^- \times M^+$ has a compatible structure of \mathbb{B} -analytic manifold. Then it is not difficult to see that there exists a unique structure of \mathbb{B} -analytic manifold on M such that a \mathbb{B} -holomorphic mapping $f: N \rightarrow M$ of \mathbb{B} -analytic manifolds is \mathbb{B} -analytic if and only if the composite map $\varphi \circ f$ (φ being as in Theorem 3.1) is \mathbb{B} -analytic. \square

Lemma 3.4. *Let V be a free \mathbb{B} -module of rank N . Every system of \mathbb{B} -linearly independent vectors (v_1, \dots, v_n) can be extended to a basis of V .*

Proof. We proceed by induction on n . If $n = 1$ and $N = 1$, it is immediate that v_1 is linearly independent if and only if v_1 is invertible. If $n = 1$ and $N \geq 2$, then either v_1 has an invertible component or it can be written as $v_1 = (1 + j)u_1 + (1 - j)u_2$ in a basis (u_1, \dots, u_N) of V . In both cases we can conclude. In the general case the above argument proves that $V/\mathbb{B} \cdot v_1$ is a free \mathbb{B} -module of rank $N - 1$, and the cosets $(\bar{v}_2, \dots, \bar{v}_n)$ are linearly independent. The proof is thus finished by simply applying the induction hypothesis. \square

Theorem 3.5. *If a $2n$ -dimensional \mathbb{B} -manifold M admits a \mathbb{B} -immersion into an affine space (\mathbb{B}^N, J) , then for every $x \in M$ global functions $F_1, \dots, F_n \in \mathbb{B}^\infty(M)$ exist such that $(d_x F_1, \dots, d_x F_n)$ is a basis of $T_x^{*1,0}(M)$. If M is compact, the converse is also true.*

Proof. Let $F_i = P_i + jQ_i$, $1 \leq i \leq N$, be the components of a \mathbb{B} -holomorphic mapping $F: M \rightarrow \mathbb{B}^N$. According to Proposition 2.9, for every $x \in M$, we can consider a system of \mathbb{B} -coordinates $z_h = x_h + jy_h$, $1 \leq h \leq n$, around x . Let A be the $N \times n$ matrix $A = (\partial P_i / \partial x_h(x))$, and let B be the $N \times n$ matrix $B = (\partial P_i / \partial y_h(x))$. The Jacobian of F at x is

$$\Lambda = \begin{pmatrix} A & B \\ B & A \end{pmatrix},$$

since F is \mathbb{B} -holomorphic. Hence F is an immersion if and only if $\text{rank } \Lambda = 2n$. Moreover the matrix of the covectors $d_x F_1, \dots, d_x F_N$ in the basis $(d_x z_1, \dots, d_x z_n)$ is ${}^t A + j {}^t B$, thus proving that the columns of $A + jB$ are \mathbb{B} -linearly independent. We conclude by applying Lemma 3.4. Conversely, if M satisfies the condition of the theorem, there are a finite open covering (U_1, \dots, U_r) of M , and functions $F_1^\alpha, \dots, F_n^\alpha \in \mathbb{B}^\infty(M)$, such that for every $\alpha = 1, \dots, r$, $(F_1^\alpha|_{U_\alpha}, \dots, F_n^\alpha|_{U_\alpha})$ is a \mathbb{B} -holomorphic coordinate system. It follows that the \mathbb{B} -holomorphic mapping $F: M \rightarrow \mathbb{B}^{rn}$, whose components are F_h^α , is an immersion. \square

Remark 3.6. (1) Wazewsky [17] obtained a one-dimensional C^∞ -foliation \mathcal{F}^+ on \mathbb{R}^2 such that every global first integral of \mathcal{F}^+ is a constant. Let \mathcal{F}^- be the orthogonal foliation with respect to the Euclidean metric. We thus define a \mathbb{B} -structure on the plane which does not admit any immersion into \mathbb{B}^N , as

follows from §2.(d) and Theorem 3.5. (2) Compact examples are easy to show: The torus $S^1 \times S^1$ with the foliations spanned by $X_1 = \partial/\partial\theta_1 + \alpha_1\partial/\partial\theta_2$, $X_2 = \partial/\partial\theta_1 + \alpha_2\partial/\partial\theta_2$, where α_1, α_2 are two distinct irrational numbers.

Proposition 3.7. *If $\varphi: M \rightarrow M'$ is a J -holomorphic map of \mathbb{B} -manifolds, then for every $x_0 \in M$ we have $\varphi(\mathcal{F}_{x_0}^-) \subseteq \mathcal{F}_{\varphi(x_0)}^-$, $\varphi(\mathcal{F}_{x_0}^+) \subseteq \mathcal{F}_{\varphi(x_0)}^+$.*

Proof. We first prove that there exists an open neighbourhood U of $x_0 \in M$ such that $\varphi(\mathcal{F}_{x_0}^- \cap U) \subseteq \mathcal{F}_{\varphi(x_0)}^-$. From §2.(d) and Proposition 2.9 it follows that an open neighbourhood V of $\varphi(x_0)$ and functions $F_i = (1+j)f_i + (1-j)g_i \in \mathcal{B}_M^\infty(V)$, $1 \leq i \leq n$, exist such that $\mathcal{F}_{\varphi(x_0)}^- \cap V = \{y \in V : f_i(y) = 0, 1 \leq i \leq n\}$, and from §2.(d) and Proposition 2.10 we know that $f_i(\varphi(x)) = f_i(\varphi(x_0))$ for $x \in \mathcal{F}_{x_0}^- \cap U$, where U is the connected component of $\varphi^{-1}(V)$ through x_0 . Let x_1 be another arbitrary point in $\mathcal{F}_{x_0}^-$, and let $\sigma: [0, 1] \rightarrow \mathcal{F}_{x_0}^-$ be a continuous arc such that $\sigma(0) = x_0$, $\sigma(1) = x_1$. We denote by S the subset of $t \in [0, 1]$ such that $\varphi(\sigma[0, t]) \subset \mathcal{F}_{\varphi(x_0)}^-$. By virtue of the first part of the proof, S contains the origin and it is open, as $t_0 \in S$ implies $\varphi(\sigma(t_0)) \in \mathcal{F}_{\varphi(x_0)}^- = \mathcal{F}_{\varphi(\sigma(t_0))}^-$, and hence for small enough $\varepsilon > 0$ each $\sigma(t)$ with $|t - t_0| < \varepsilon$ lies on a neighbourhood of $\sigma(t_0)$ in the leaf $\mathcal{F}_{\sigma(t_0)}^-$, which is mapped by φ into $\mathcal{F}_{\varphi(x_0)}^-$. Moreover, S is also closed. In fact, assume that $t_0 \in \bar{S}$. If $\varphi(\sigma(t_0)) \notin \mathcal{F}_{\varphi(x_0)}^-$, then for every small enough $\varepsilon > 0$, we have $\varphi(\sigma(t)) \in \mathcal{F}_{\varphi(\sigma(t_0))}^-$ for $|t - t_0| < \varepsilon$; but we know that a point $t_0 - \varepsilon$ exists such that $\varphi(\sigma(t_0 - \varepsilon))$ belongs to $\mathcal{F}_{\varphi(x_0)}^-$. As $\mathcal{F}_{\varphi(x_0)}^- \cap \mathcal{F}_{\varphi(\sigma(t_0))}^- = \emptyset$, this leads one to a contradiction. The proof for the positive leaf is similar. \square

Theorem 3.8. *Let M be a \mathbb{B} -manifold of real dimension $2n$. We have (1) If for every $x \in M$ there exists global functions $F_1, \dots, F_n \in \mathcal{B}^\infty(M)$ such that $(d_x F_1, \dots, d_x F_n)$ is a basis of $T_x^{*1,0}(M)$, then the foliations $T^-(M)$ and $T^+(M)$ are regular. Hence, the leaves of $T^-(M)$ and $T^+(M)$ are closed submanifolds of M . (2) If M is an embedded \mathbb{B} -submanifold of an affine space (\mathbb{B}^N, I) , then the quotient manifolds $M/T^-(M)$, $M/T^+(M)$ are Hausdorff spaces.*

Proof. (1) By virtue of the hypothesis, for every $x \in M$ there exist an open neighbourhood U of x , and global functions $F_i \in \mathcal{B}^\infty(M)$, $1 \leq i \leq n$, such that $(F_i|_U)$ is a \mathbb{B} -coordinate system. From §2.(d), we can write $F_i = (1+j)f_i + (1-j)g_i$, $1 \leq i \leq n$, where f_i and g_i are first integrals of $T^-(M)$ and $T^+(M)$, respectively. Since

$$dF_1 \wedge \dots \wedge dF_n = 2^{n-1}(1+j)df_1 \wedge \dots \wedge df_n + 2^{n-1}(1-j)dg_1 \wedge \dots \wedge dg_n,$$

substituting $f_i - f_i(x)$ for f_i and $g_i - g_i(x)$ for g_i , and shrinking U if necessary, we can assume that $(f_1, \dots, f_n, g_1, \dots, g_n)$ is a cubical coordinate system centered at $x \in M$, which is flat ([13, I. §2]) with respect to $T^+(M)$. Similarly, $(g_1, \dots, g_n, f_1, \dots, f_n)$ is a cubical coordinate system centered at $x \in M$, which is flat with respect to $T^-(M)$. We have to prove that if a leaf \mathcal{F}^+ of $T^+(M)$ intersects U , then $\mathcal{F}^+ \cap U$ is contained in a unique n -dimensional slice of

$(U; f_1, \dots, f_n, g_1, \dots, g_n)$. As \mathcal{F}^+ is connected and g_1, \dots, g_n are first integrals of $T^+(M)$, we conclude that $g_i|_{\mathcal{F}^+}$ is constant, *i.e.*, there exist $\lambda_1, \dots, \lambda_n \in \mathbb{R}$ such that $g_i|_{\mathcal{F}^+} = \lambda_i$, $1 \leq i \leq n$, and the result follows. The last assertion follows from [13, I.§4.Theorem VII]. (2) Let $\phi: M \rightarrow \mathbb{B}^N$ be a \mathbb{B} -embedding. By virtue of Theorem 3.5 and the part (1) of the present theorem, we know that the foliations induced by $T^-(M)$, $T^+(M)$ are regular. Let $p^\mp: \mathbb{B}^N \rightarrow \mathbb{B}^N/T^\mp(\mathbb{B}^N) = \mathbb{R}^N$ be the canonical projections. We prove that $p^\mp(\phi(M))$ are embedded submanifolds of \mathbb{R}^N . In fact, as ϕ is an embedding, for every $z_0 \in M$ there exist open neighbourhoods U , $V = V^- \times V^+$ of z_0 , $\phi(z_0)$ in M , \mathbb{B}^N , respectively and a \mathbb{B} -coordinate system $F_1, \dots, F_N \in \mathcal{B}^\infty(V)$ such that $\phi(U) = \{w \in V : F_{n+1}(w) = \dots = F_N(w) = 0\}$. From §2.(d) we have $F_i(u, v) = (1+j)f_i(u) + (1-j)g_i(v)$, so

$$p^-(\phi(U)) = \{u \in V^- : f_{n+1} = \dots = f_N(u) = 0\}. \quad (3.1)$$

Hence with the topology induced from that of \mathbb{R}^N , $p^-(\phi(M))$ can be covered by coordinate open subsets $(V^-; f_1, \dots, f_N)$ so that (3.1) holds true, thus proving that $p^-(\phi(M))$ is an embedded submanifold in \mathbb{R}^N ([3, 16.8.1.1]), and similarly for $p^+(\phi(M))$. Moreover the maps $p^\mp \circ \phi: M \rightarrow (p^\mp \circ \phi)(M)$ are surjective submersions as ϕ_* transforms $T^\mp(M)$ into $T^\mp(\mathbb{B}^N)$, hence $\text{Ker}(p^\mp \circ \phi)_* = T^\mp(M)$, and thus $\dim \text{Im}(p^\mp \circ \phi)_* = n = \dim(p^\mp \circ \phi)(M)$. As $\phi(\mathcal{F}_z^\mp) \subseteq \mathcal{F}_{\phi(z)}^\mp$, we conclude that $p^\mp(\phi(M))$ can be identified with the quotient manifolds $M/T^\mp(M)$. \square

Definition 3.9. A \mathbb{B} -manifold is said to be a *Stein \mathbb{B} -manifold* if M satisfies the following three conditions (*cf.* [8, 5.1.3]): (α) M is \mathbb{B} -convex; *i.e.*, $\hat{K} = \{x \in M : |F(x)| \leq \sup_K |F|, \forall F \in \mathcal{B}^\infty(M)\}$ is compact for every compact subset $K \subseteq M$. (β) If $x_1 \neq x_2$ are two points in M , then there exists $F \in \mathcal{B}^\infty(M)$ such that $F(x_1) \neq F(x_2)$. (γ) For every $x \in M$, there exist n functions $F_1, \dots, F_n \in \mathcal{B}^\infty(M)$ which form a coordinate system at x .

Remark 3.10. (1) From Theorem 3.5, it follows that every \mathbb{B} -manifold M admitting an immersion into an affine space \mathbb{B}^N , satisfies the condition (γ). (2) (\mathbb{B}^N, I) is a Stein \mathbb{B} -manifold: (β) and (γ) are trivial and (α) follows from the formula $\hat{K} = p^-(K) \times p^+(K)$, where $p^\mp: \mathbb{B}^N = \mathbb{R}^N \times \mathbb{R}^N \rightarrow \mathbb{R}^N$ are the canonical projections, as follows from Example 2.11. (3) As in the complex case (*e.g.*, see [7, VII.A.Examples (6)]) and taking the first remark above into account, it follows that any closed \mathbb{B} -submanifold of \mathbb{B}^N is a Stein \mathbb{B} -submanifold.

4 The embedding theorem

Theorem 4.1. *A connected \mathbb{B} -manifold M is embeddable as a closed \mathbb{B} -submanifold of an affine space (\mathbb{B}^N, I) if and only if M is a Stein \mathbb{B} -manifold and the quotient manifolds $M^- = M/T^-(M)$, $M^+ = M/T^+(M)$ are Hausdorff spaces.*

Proof. Assume that M is a closed \mathbb{B} -submanifold of \mathbb{B}^N . From Remark 3.10 above it follows that M is a Stein \mathbb{B} -manifold and from Theorem 3.8-(2), we also conclude that M^\mp are Hausdorff spaces. Conversely, assume that both

conditions of the statement hold true for M . Then, by virtue of Theorem 3.1 we know that the map $\varphi: M^- \times M^+, \varphi(x) = (\mathcal{F}_x^-, \mathcal{F}_x^+)$, is an open \mathbb{B} -embedding. We first prove that φ is a \mathbb{B} -diffeomorphism. For every subset $S \subset M$, we set $S^- = p^-(S)$, $S^+ = p^+(S)$, where $p^\pm: M \rightarrow M^\pm$ stand for the canonical mappings. As φ is an open embedding we identify M to $\varphi(M)$, thus assuming that φ is the inclusion. If there exists a relatively compact open subset $U \subset M$, such that $\bar{U}^- \times \bar{U}^+ \not\subset M$ (and hence $(\bar{U}^- \times \bar{U}^+) \cap M \neq \emptyset$, as $\bar{U} \subset \bar{U}^- \times \bar{U}^+$ and $(\bar{U}^- \times \bar{U}^+) \cap (\mathbb{B}^N - M) \neq \emptyset$), then M is not \mathbb{B} -convex. In fact, picking a point $x \in \partial M \cap (\bar{U}^- \times \bar{U}^+)$ we obtain a sequence $x_i \in (\bar{U}^- \times \bar{U}^+) \cap M$ converging to x . Therefore, we have a sequence in $\hat{\bar{U}}$ that has no convergent subsequence in $\hat{\bar{U}}$, and accordingly, $\hat{\bar{U}}$ is not compact. It thus follows that for every relatively compact open subset $U \subset M$, we have $\bar{U}^- \times \bar{U}^+ \subseteq M$. Let $(U_i)_{i \in \mathbb{N}}$ be a sequence of relatively compact subsets such that $\bar{U}_i \subset U_{i+1}$, $M = \bigcup_{i \in \mathbb{N}} \bar{U}_i$. Given $x^- \in M^-$, $y^+ \in M^+$, let $x, y \in M$ be two points such that $p^-(x) = x^-$, $p^+(y) = y^+$, so that $x = (x^-, x^+)$, $y = (y^-, y^+)$. For a large enough i , we have $x, y \in \bar{U}_i$, and since $\bar{U}_i^- \times \bar{U}_i^+ \subset M$, we conclude that $(x^-, y^+) \in M$, and hence $M = M^- \times M^+$. According to Whitney's embedding theorem, M^- and M^+ can be embedded as closed submanifolds of \mathbb{R}^{2n+1} . Then, we have a closed \mathbb{B} -embedding $M \rightarrow \mathbb{B}^{2n+1}$ defined as the composite map $M \xrightarrow{\varphi} M^- \times M^+ \hookrightarrow \mathbb{R}^{2n+1} \times \mathbb{R}^{2n+1} = \mathbb{B}^{2n+1}$, thus finishing the proof. \square

Remark 4.2. (1) If the real dimension of M is $2n$, then we can take $N = 2n + 1$. (2) As an example, it follows from the above theorem that the unit open disc $\Delta(0, 1)$ in \mathbb{B} and the unit open square $(-1, 1)^2$ in \mathbb{B} are not \mathbb{B} -diffeomorphic as $\Delta(0, 1)$ cannot be embedded into any \mathbb{B}^N for condition (α) in Definition 3.9 does not hold true for $\Delta(0, 1)$, whereas $(-1, 1)^2$ is evidently \mathbb{B} -diffeomorphic to \mathbb{B} . (3) We also remark that, as the above proof shows, every closed \mathbb{B} -submanifold of (\mathbb{B}^N, I) is a product manifold $X \times Y$, $\dim X = \dim Y$, with the \mathbb{B} -structure given in Example 2.11.

References

- [1] W. Bertram, *Complexifications of symmetric spaces and Jordan theory*, Trans. Amer. Math. Soc. **353** (2001), 2531–2556.
- [2] V. Cruceanu, P. Fortuny, and P.M. Gadea, *A survey on Paracomplex Geometry*, Rocky Mountain J. Math. **26** (1996), 83–115.
- [3] J. Dieudonné, *Éléments d'Analyse*, volume III, Gauthier-Villars, Paris, 1970.
- [4] S. Erdem, *Paracomplex projective models and harmonic maps into them*, Beiträge Algebra Geom. **40** (1999), 385–398.
- [5] P.M. Gadea and J. Muñoz Masqué, *A-differentiability and A-analyticity*, Proc. Amer. Math. Soc. **124** (1996), 1437–43.

- [6] P.M. Gadea, J. Grifone, and J. Muñoz Masqué, *Manifolds modelled over free modules over the double numbers*, Acta Math. Hungar. (to appear).
- [7] R.C. Gunning and H. Rossi, *Analytic functions of several complex variables*, Prentice Hall, Englewood Cliffs, N.J., 1965.
- [8] L. Hörmander, *An introduction to complex analysis in several variables*, North-Holland, Amsterdam, 1973.
- [9] S. Kaneyuki, *On a remarkable class of homogeneous symplectic manifolds*, Proc. Japan Acad. Ser. A Math. Sci. **67** (1991), 128–131.
- [10] S. Kaneyuki and M. Kozai, *Paracomplex structures and affine symmetric spaces*, Tokyo J. Math. **8** (1985), 81–98.
- [11] P.W. Ketchum, *Analytic functions of hypercomplex variables*, Trans. Amer. Math. Soc. **30** (1928), 641–667.
- [12] G. Olafsson, *Symmetric spaces of Hermitian type*, Differential Geom. Appl. **1** (1991), 195–233.
- [13] R.S. Palais, *A global formulation of the Lie theory of transformation groups*, Mem. Amer. Math. Soc., **22**, 1957.
- [14] V.V. Shurygin, *Manifolds over algebras and their application to the geometry of jet bundles*, Uspekhi Mat. Nauk **48** (1993), 75–106; Russian Math. Surveys **48** (1993), 75–104.
- [15] W.C. Waterhouse, *Analyzing some generalized analytic functions*, Exposition. Math. **10** (1992), 183–192.
- [16] —, *Differentiable functions on algebras and the equation $\text{grad}(w) = M \text{grad}(v)$* , Proc. Roy. Soc. Edinburgh, Sect. A **122** (1992), 353–361.
- [17] T. Wazewsky, *Sur l'équation $Pp+Qq=0$* , Mathematica **8** (1934), 103–116; **9** (1935), 179–182.
- [18] R. Z. Yeh, *Analysis and applications of holomorphic functions in higher dimensions*, Trans. Amer. Math. Soc. **345** (1994), 151–177; **347** (1995), 1081.

Authors' addresses:

P.M.: Institute of Mathematics and Fundamental Physics, CSIC, Serrano 144, 28006 Madrid, Spain. *e-mail*: pmgadea@iec.csic.es
 J.G.: Laboratoire Emile Picard C.N.R.S., Université Paul Sabatier, 118 Route de Narbonne, 31062 Toulouse, Cedex (France). *e-mail*: grifone@picard.ups-tlse.fr
 J.M.: Inst. of Applied Physics, CSIC, Serrano 144, 28006 Madrid, Spain. *e-mail*: jaime@iec.csic.es